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Cyclic Aggradation and Downcutting, Fluvial Response to Volcanic Activity, and Calibration of Soil-Carbonate Stages in the Western Grand Canyon, Arizona

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In the western Grand Canyon, fluvial terraces and pediment surfaces, both associated with a Pleistocene basalt flow, document Quaternary aggradation and downcutting by the Colorado River, illuminate the river's response to overload and the end of overload, and allow calibration of soil-carbonate stages and determination of downcutting rates. Four downcutting–aggradation cycles are present. Each begins with erosion of older deposits to form a new river channel in which a characteristic suite of deposits is laid down. The current cycle (I) started ~700 yr B.P. The oldest (IV) includes the 603,000 ± 8000 to 524,000 ± 7000 yr Black Ledge basalt flow, emplaced when the river channel was ~30 m higher than it is now. The flow is overlain by basalt–cobble gravel and basalt sand. Soils reach the stage V level of carbonate development. Calibrated ages for soil stages are Stage V, ~525,000 yr; stage IV, <525,000 yr, ≥250,000 yr; stage III, <250,000 yr, ≥100,000 yr. The monolithologic basalt sand beds represent overloading by volcanic ash produced by an eruption 30–50 km upstream. The basalt–cobble beds signal breaching and rapid destruction of lava dams and erosion of flows. These deposits show that the Colorado River responds to overload by aggrading vigorously during the overload and then downcutting equally vigorously when the overload ends. The overall downcutting rate for the interval studied is 1.6 cm/1000 yr, much lower than rates upstream. The current downcutting rate, 11–14 m/1000 yr, likely is a response both to the end of late Pleistocene and early Holocene overload and to the reduction of sediment supply caused by Glen Canyon Dam.

Key Words: **volcanism; soil carbonates; Arizona; Grand Canyon; cyclic stream response.**

Supplementary material for this article may be found on the journal home page (http://www.academicpress.com/qr).

INTRODUCTION

Our work in the Granite Park area (Fig. 1) began in 1993. This area was chosen because it is one of the few places in the lower Grand Canyon that contains extensive Quaternary deposits and surfaces of various ages, which locally are associated with archeological remains. Also present are Quaternary basalt flows that can be dated with precision by means of laser-fusion $^{40}Ar–^{39}Ar$ techniques, providing a means for calibrating the methods used for determining ages of Quaternary features elsewhere in the Grand Canyon. Another aim was to investigate whether the fluvial and near-fluvial morphostratigraphy developed in the eastern Grand Canyon is valid in the western Grand Canyon, where the fluvial system has been disrupted repeatedly by Quaternary basalt flows cascading into the canyon from the area of Vulcan's Throne–Whitmore Canyon (river miles 179 to 188,[1] 30 to 20 river miles upstream from Granite Park). Finally, we were interested in determining whether the known volcanic events that influenced the river in

[1] Distances in the Grand Canyon are measured in miles along the river from the gaging station at Lees Ferry, Arizona, which is the point of beginning for most river trips.

the lower Grand Canyon can shed light on the river's response to a changing balance between over- and underloading by sediment. Preliminary results of the investigation were summarized in Lucchitta *et al.*, 1995a.

The Grand Canyon is the result of vigorous downcutting that started about 5 myr ago (Lucchitta, 1972, 1988, 1990). The overall downcutting has been interrupted several times during the Quaternary by episodes of aggradation, probably caused by climatically controlled overloading of the river with sediment (Machette and Rosholt, 1991; Lucchitta *et al.*, 1995b).

Each episode of aggradation is marked by deposits and surfaces that attest to the position of the floodplain at the end of aggradation. This position, or "level," as used in this paper, is identified by remnants of fluvial terraces or pediment surfaces graded to the terraces.

Each downcutting–aggradation couplet represents a cycle, the deposits and surfaces of which are entrenched into those of previous cycles. Downstream from the lava cascades in the Toroweap area, this orderly scheme is modified by the results of volcanic events such as ash falls accompanying eruptions and the emplacement of basalt flows, some of which coursed down the canyon for many tens of kilometers. Other flows formed dams that impounded the Colorado River but were eventually overtopped and rapidly eroded to the predam river grade.

The Granite Park area is well suited to studying the interaction between rivers of lava and the river of water, because it has a relatively simple and orderly stratigraphy that is promising for sorting out relations between volcanic products, sedimentary deposits, and geomorphic features. These relations, in turn, provide an opportunity to understand how rivers function during extreme overloading or very-high-energy discharge. The lava also provides a means for dating associated soils and for determining downcutting rates.

METHODS

Five profiles of the geologic section span the river interval between Miles 207.3 and 208.8. These profiles are situated where the Quaternary deposits are thickest and best exposed (Fig. 1). Geologic units and their relationships were described, as were the soils developed on the units. The elevations of contacts and locations of soil descriptions were determined by means of a total station situated at two instrument stations (Fig. 1). Selected units were sampled for soil analyses, paleomagnetism, and radiometric age determinations.

Results from the field determinations are plotted on five cross sections (Figs. 2–6), which are drafted to scale in the vertical direction using the total-station data. The vertical scale gives accurate figures for the elevation of important geologic contacts above the high-water line (HWL), which is a reference datum representing the highest level generally reached by the river during the fluctuating-flow regimen that was in force for many years after construction of Glen Canyon Dam. The HWL corresponds to about 850 m^3/s (30,000 cfs)[2] and is marked in the field by the lowest bushes and small trees above the river. The surface of the river itself cannot be used as a datum because of its variability. Horizontal distances are not to scale.

All levels including and above level 3 (archeological unit; Appendix A[3]) were examined informally for development of soil horizons in cleaned-up natural exposures. Only two formal descriptions were done (Appendix B), owing to the limited time in the area. These involved digging soil pits and then describing, sampling, and analyzing the soils according to standards of the National Cooperative Soil Survey (Soil Survey staff, Soil Conservation Service, 1993). Laboratory analyses for particle size distribution and percentages of carbonate, aluminum, and iron were carried out by Dr. Randy Southard, University of California at Davis. Soils were classified according to Soil Taxonomy (Soil Survey Staff, 1994). Classification of secondary carbonate development follows Gile *et al.* (1981), modified by Machette (1985).

Seven samples of the Black Ledge basalt flow were collected from various locations (Figs. 1, 3, 4, and 5). ^{40}Ar–^{39}Ar plateau ages were determined by whole-rock stepwise incremental laser heating and fusion carried out at the Berkeley Geochronology Center. See Appendix C for procedures, analytical data, step-heating spectra, and isochrons.

RESULTS

Geology and Geomorphology

The Granite Park area contains Quaternary units exposed over an 83-m interval that span more than 600,000 years of time, as determined by radiometric ages and degree of soil development. In the eastern Grand Canyon, this time span is represented by units exposed over a greater vertical interval (Lucchitta *et al.*, 1995b).

The most conspicuous Quaternary geologic unit in the Granite Park area is a basalt composed of several intracanyon flow units whose exposed and preserved thickness is as great as 30 m. Mostly, the flows are separated by little or no sediment. In places, however, as much as 3.5 m of gravel and debris is interbedded with the upper flows. The thickest flow units have a well-developed coarse columnar structure. These are the farthest traveled of the intracanyon lavas and collectively are equivalent to the "Black Ledge flow" of Hamblin (1994), who treated them as a single flow.

The seven samples analyzed document an age of ~604,000 yr for the main part of the Black Ledge flow and ~524,000 yr for the thin flow within sediment overlying the main part (Fig. 5). Both were mapped as the Black Ledge flow by Hamblin (1994), who reports an age (obtained by P. Damon) of 549,000 ± 32,000 yr. The level from which the sample was

[2] USGS gage data are in cubic feet/second (cfs). 1 m^3 ≈ 35 cfs.

[3] Appendixes A, B, and C are available as supplementary material on the journal home page.

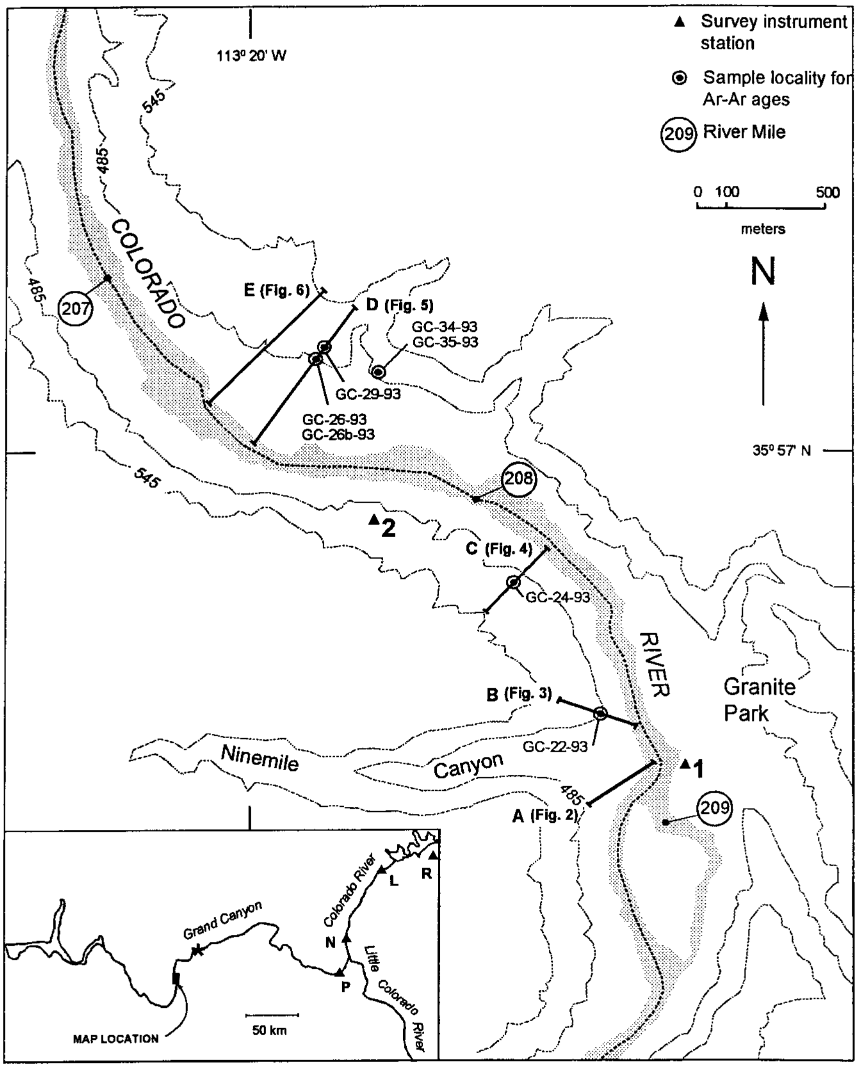

FIG. 1. Map of the Granite Park area showing cross section lines, instrument stations, and sample localities for ^{40}Ar–^{39}Ar ages. River level in area of sections is at approximately 425 m altitude. Shaded area denotes the present channel of the Colorado River. In inset map, asterisk denotes the source of lavas in the Vulcan's Throne–Whitmore Wash area; triangles denote areas studied in the eastern Grand Canyon. P, Palisades–Comanche; N, Nankoweap; L, Lees Ferry; R, Rainbow Plateau.

obtained is not specified. Dalrymple and Hamblin (1998) sampled the flow but did not date it because of excessive glass in the samples.

Other notable units include: (1) river gravel that forms steep bluffs near the river; (2) coarse black sand composed predominantly or exclusively of generally cross bedded basaltic ash; and (3) basalt–cobble gravel, commonly well rounded, that includes scarce ($<1\%$) clasts of Paleozoic rocks, quartz, quartzite, igneous rocks, and other lithologies typical of Colorado River gravels. The basalt–cobble gravel, as a unit, mostly overlies the basalt sand. However, the gravel units commonly include some sand and the sand units some cobbles. Basaltic gravel and sand are variously present directly above the basalt flows, between flows, and inset into the flows. None of the volcanic units is present upstream from Vulcan's Throne.

Sloping planation surfaces (pediments) at various levels are present throughout the area (Figs. 2–6). Some toe downslope into river gravel or basalt. Their "level" is defined by elevation above the river and relation to other surfaces. Many surfaces display carbonate-enriched soils whose degree of enrichment increases with topographic elevation and the level of the surface.

The Granite Park section includes nonvolcanic Quaternary features present along the river upstream from Vulcan's Throne. Notable are various river terraces, the fine to very fine sand of the archeological unit, debris-flow terraces along major washes, and deposits and terraces associated with the most recent downcutting by the Colorado River.

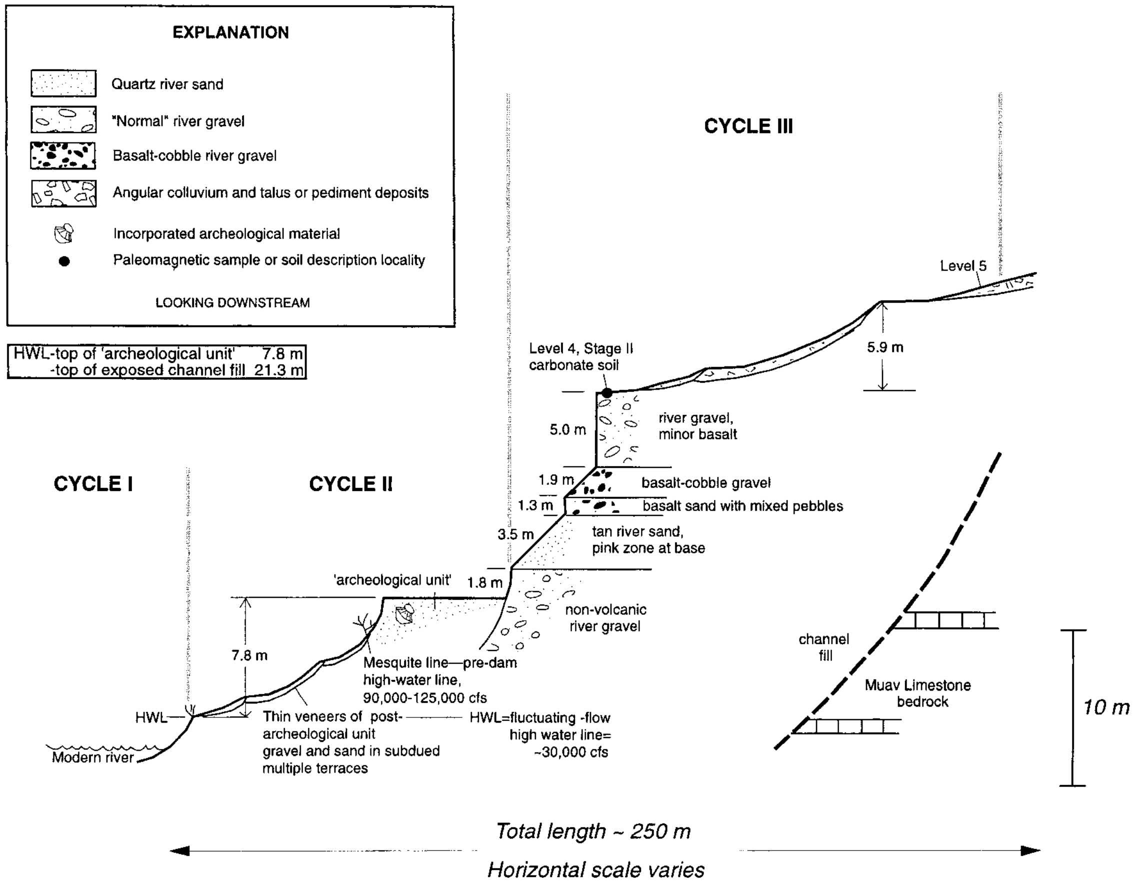

FIG. 2. Profile A, Granite Park, river right, River Mile 208.8. Here and in all other sections, vertical gray bars separate cycles, and horizontal black lines denote boundaries of intervals (shown in meters). The ~10-m-thick archeological unit (Lucchitta *et al.*, 1995b) contains abundant archeological material (through Pueblo II) in the upper part, which also has charcoal layers, many of which contain cultigen pollen, attesting to farming by prehistoric people (Lucchitta *et al.*, 1995b; S. Davis *et al.*, unpublished data). Deposition began before ~5100 yr B.P. (Lucchitta and Leopold, 1999) and perhaps as much as ~13,500 yr B.P. on regional grounds (Lucchitta *et al.*, 1995b, and unpublished data). Hereford *et al.* (1993) report an Archaic hearth (~2000 yr B.P.) in the deposit at River Mile 69. Deposition ended ~1250 A.D. because Pueblo II artifacts and sites (Fairley *et al.*, 1994) occur both in the upper part and on top of the unit. Modern downcutting amounts to ~10 m. The "mesquite line" is the lower limit for large and abundant mesquite trees and corresponds to the common pre-Glen Canyon Dam flood discharges in the 2500–4000 m^3/s (90,000–140,000 cfs) range. Strandlines and minor terraces below the line mark postdam floods.

Sections A–E, measured in the Granite Park area (Fig. 1), depict these features and contain the record from which river processes can be reconstructed. The most conspicuous of these processes are downcutting–aggradation cycles, of which four principal ones are recorded. Cycle IV is the oldest. Each cycle begins with excavation of older deposits, forming a new river channel lower than preexisting ones. The channel is then filled with a characteristic sequence of aggradational deposits. The cycle ends when deposition stops. As downcutting resumes, initiating the next cycle, the deposits are eroded, in most cases quickly. If downcutting halts at some level, sloping erosion surfaces graded to that level are formed in favorable places along the sides of the river valley. Several such surfaces, at different levels, may be formed as downcutting progresses. These surfaces belong to the next (younger) cycle, even if shown within the field of an older cycle in the profiles (Figs. 2–6).

Soils

Soils on the frequently to occasionally flooded surfaces near the river (Cycle I) are Entisols, showing little or no pedogenesis. Stage I soils on the archeological unit (Cycle II) are deep and sandy textured, with stratified charcoal layers and associated pollen from cultigen taxa.

Stage II soils (Machette, 1985; Gile *et al.*, 1981) are developed on pediment level 4 (Cycle III) and were examined qualitatively. These soils have secondary calcium carbonate as thin coatings lining the underside of pebbles and cobbles and as common small- to medium-size concretions within a moderately developed K horizon at shallow depth (5–15 cm).

Stage III carbonate is developed on pediment level 5 (description and data in Appendix B).

A stage IV (Machette, 1985) petrocalcic horizon with platy structure is present on pediment level 6 (inset, section E, Fig.

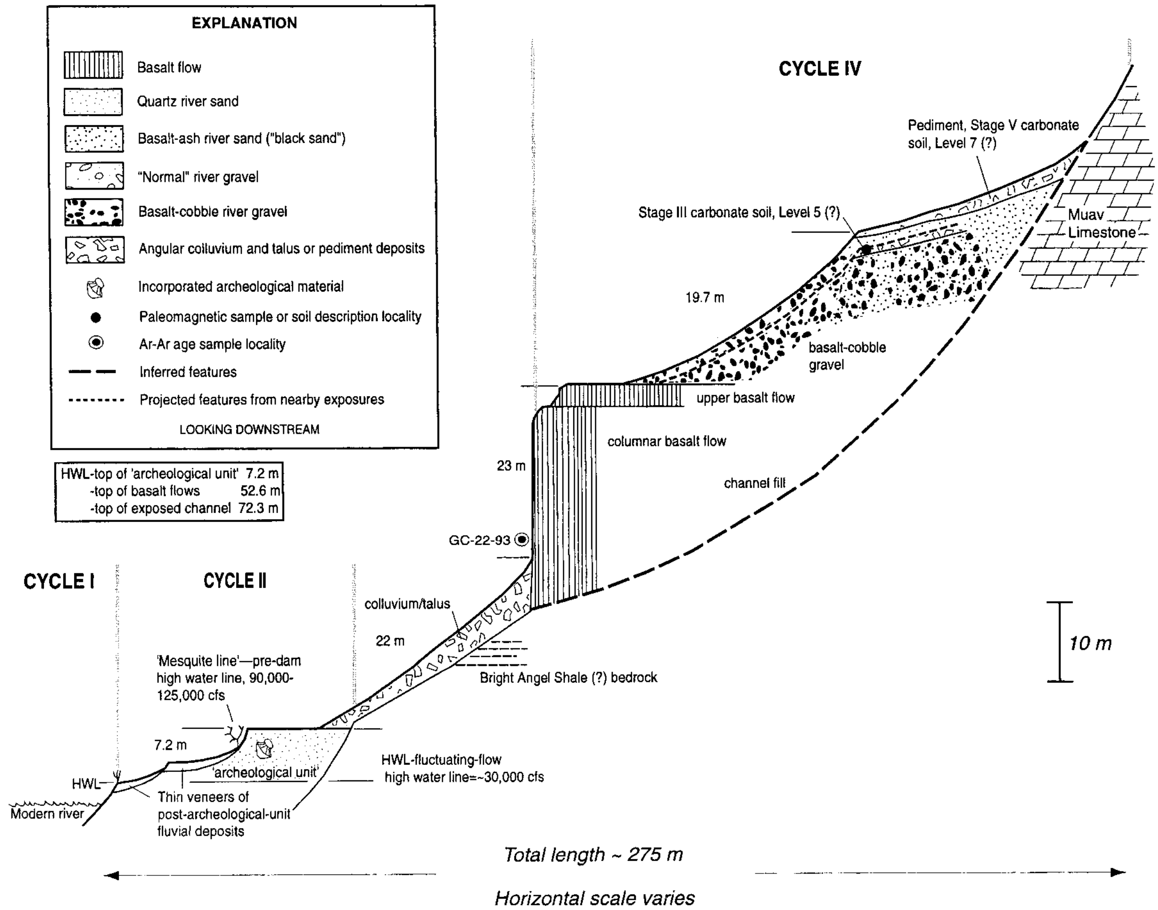

FIG. 3. Profile B, Granite Park, river right, River Mile 208.7. Area between gray bars delimiting Cycles II and IV is underlain by colluvium over bedrock; no alluvial cycle here.

6). No good natural exposures were found, and time constraints precluded hand excavation in these calcretes.

A calcrete that displays the calcium carbonate distribution and features of Stage V (Machette, 1985)[4] was observed at pediment level 7 in section D (Fig. 5) and is well exposed on that level in cross section B (Fig. 3), where it was examined in detail at an escarpment exposure along a drainage swale (description and data in Appendix B). The calcrete was not slabbed to detect pisolites, but these are presumed to be present in view of the thickness, platiness, and secondary calcium carbonate content of the calcrete layer. The calcrete is exposed over 3–5% of the surface, indicating accelerated erosion in comparison to that on younger pediments.

[4] Using the classification of Machette (1985, Table 1), in which Stage V requires >50% carbonate content in high-gravel soils, a thickness of 1–2 m for the carbonate layer, strong platy to tabular structure, and laminae thicker than 1 cm. Pisolithic structures may or may not be present. On the other hand, Harden *et al.* (1985, Table 2) consider incipient development of pisolithic structures characteristic of Stage V. Pisolithic structures were not observed in our limited examination, but this does not prove their absence. The soil of level 7 is either a very advanced Stage IV or an early Stage V. In our opinion, the data are more in keeping with a Stage V.

DISCUSSION AND INTERPRETATIONS

Geology and Geomorphology

The Quaternary record in the Granite Park area consists of four fluvial cycles. Cycle I is the modern river channel and its fill of gravel and sand, which record modern activities of the Colorado River, including features produced by large pre-Glen Canyon Dam floods.

During Cycle II, the channel was filled by more than 10 m of fine and very fine sand of the archeological unit, derived locally from the Colorado Plateau (Lucchitta *et al.*, 1995b; Lucchitta and Leopold, 1999). The overload by locally derived material excluded coarser, far-traveled material from the river. This is the most recent major aggradation by the Colorado River and its tributaries. Extensive human habitation (Fairley *et al.*, 1994) and agriculture (Lucchitta *et al.*, 1995b; Davis *et al.*, 1994) took place in the Grand Canyon during this cycle.

The beginning of Cycle III was marked by cutting of the river channel into the basalt and deposits of Cycle IV to an unknown level below the present grade of the river. At least 24 m of river gravel that contains only a small percentage of

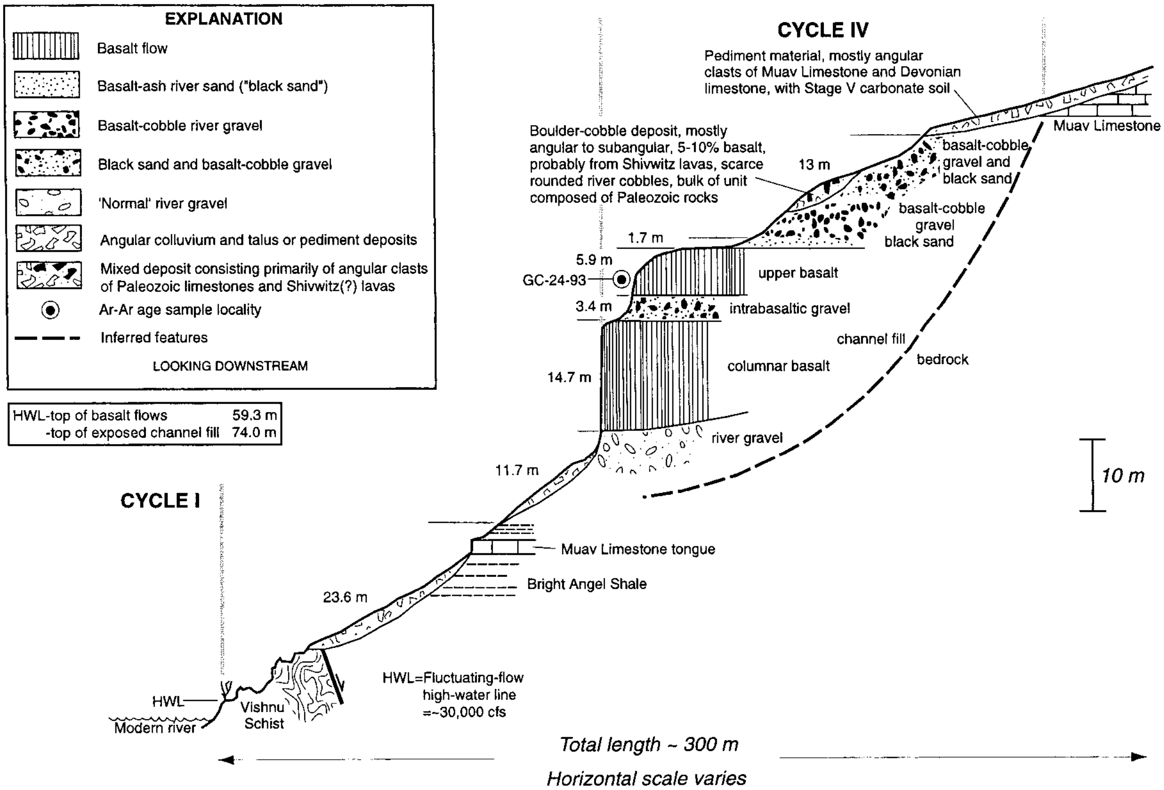

FIG. 4. Profile C, Granite Park, river right, River Mile 208.2. Area between gray bars delimiting Cycles I and IV is underlain by bedrock; no alluvial cycle here. Angular cobbles and boulders above the basalt are of Paleozoic rocks and subordinate basalt similar to that of the Shivwits Plateau to the west (Lucchitta, 1975). Rounded cobbles are scarce. Deposit probably is a debris flow issuing from an upstream canyon heading in the Shivwits Plateau.

basalt clasts (sections A, D, and E) was deposited in this channel, indicating a general absence of volcanic activity upstream during the time interval represented by accumulation of the gravel. However, section A (Fig. 2) contains units not present elsewhere, including ~3 m of basaltic sand and gravel, whose monolithologic character is not consonant with normal fluvial transport. These deposits may be evidence for a probably minor volcanic event that took place upstream after emplacement of the Black Ledge basalt flow. Such events are known to have occurred in the Vulcan's Throne–Whitmore Canyon area (Hamblin, 1994; G. H. Billingsley, personal communication, 1998). A more vigorous post-Black Ledge volcanic event is represented by the black ash and basalt–cobble gravel that overlie the nonvolcanic gravel in sections D and E (Figs. 5 and 6) and attain a preserved thickness of more than 11 m. These units are truncated by a level 4 and a level 5 surface, with Stage II and Stage III carbonate soils, respectively. In the eastern Grand Canyon, Stage II carbonate has exposure ages clustering around 80,000 yr (Table 2; Caffee *et al.,* 1994; Lucchitta *et al.,* 1995b). Weak Stage III carbonate soil yields exposure ages clustering around ~100,000 yr, and advanced Stage III carbonate has exposure ages as high as ~250,000 yr (Table 2 and Lucchitta *et al.,* 1995b). The conclusion is that carving of the Cycle III channel and the eruption that produced the black sand within it definitely predate 100,000 yr and possibly predate 250,000 yr.

Cycle IV began with carving of a channel into Vishnu and Bright Angel/Muav bedrock down to ~30 m above the present high-water line (Figs. 5 and 6). Several units of the Black Ledge basalt flow were emplaced in the channel ~600,000 yr ago (Table 1), displacing the river. The flows, which were more than 135 km long (Hamblin, 1994) and extended 54 km below the Granite Park area, filled the channel with more than 30 m of basalt (Fig. 5). The last of these flows was emplaced ~525,000 yr ago. At that time, the channel contained a thin veneer of basaltic debris overlying the little-eroded surface of the 600,000-yr flows. Evidently, the river, which was flowing on top of a thick and resistant layer of basalt for >135 km, was unable to cut through this basalt in the 75,000 yr separating emplacement of the two flow sequences. A reasonable interpretation is that the river cut through the older flow by means of falls that retreated upriver but had not reached the Granite Park area by the time the younger flow was emplaced. These falls represented the local base level for the upstream part of the river. Aggradation continued during and after emplacement of the younger flow, with accumulation of at least 27 m of basalt–cobble gravel and basalt–ash sand (Fig. 6) and minimal admixture of normal river-channel material. The absence of

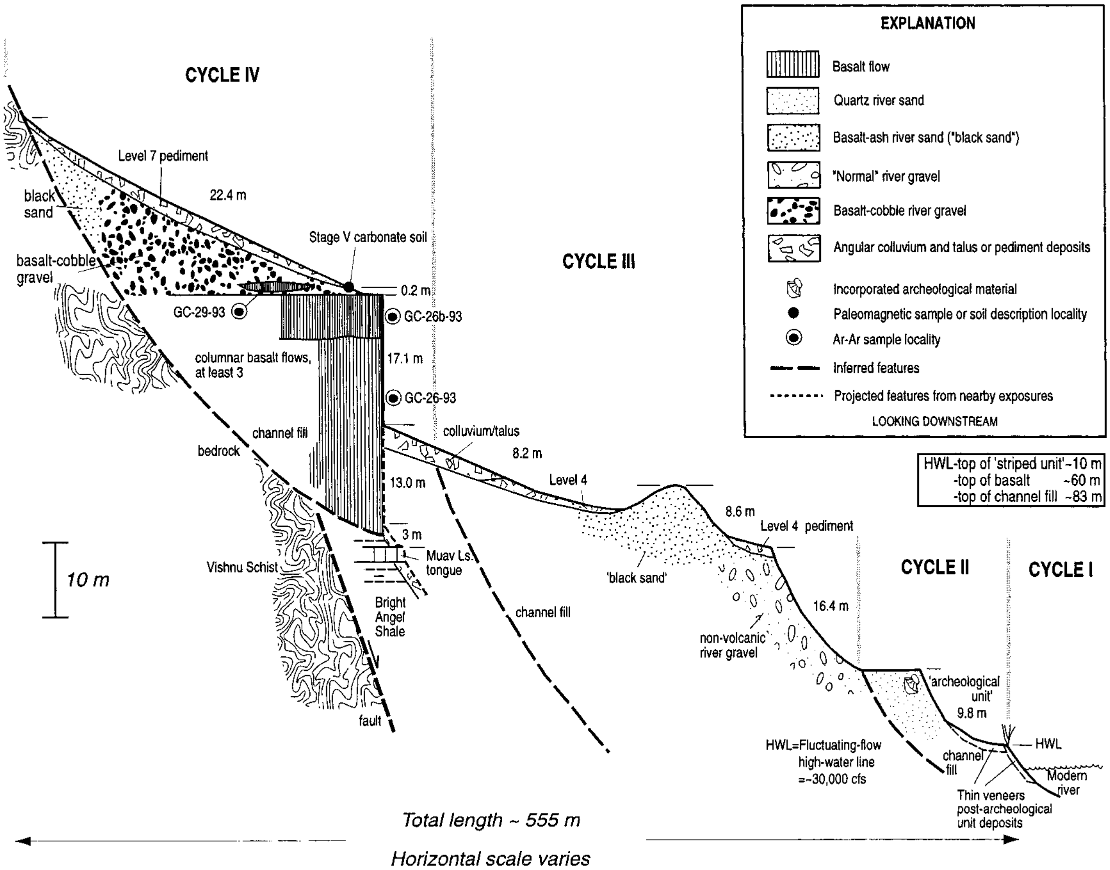

FIG. 5. Profile D, Granite Park, river left, River Mile 207.5. This is the most complete sequence of Quaternary deposits in the Granite Park area. The contact between Bright Angel Shale and Muav Limestone is projected into the line of section from a nearby gully. The location of the Cycle III channel edge is poorly constrained.

such material indicates unusual and probably catastrophic events upstream, which resulted in major accumulation of volcanic products within the river system while essentially excluding both the material that normally transits down the river channel and that introduced into the channel by tributary drainages. Such an exclusion is not easily achieved, especially over a substantial time. This makes it likely that the basalt gravel and sand were deposited quickly and just after emplacement of the 525,000-yr basalt flow. Downcutting resumed after these events. Eventually, river grade again stabilized on top of the 600,000-yr basalt flow, allowing formation of level 7 and level 6 pediments that truncate the basalt–cobble gravel and black sand and are graded to, or near to, the top of the basalt (Figs. 5–7). These surfaces have Stage V and IV carbonate soils, respectively.

The time span for Cycle IV extends from ≥600,000 yr to ≤525,000 yr ago.

Soils and Calibration of Soil-Carbonate Stages

Soils in the Granite Park area range from carbonate stage I through V. Soil stages developed at Granite Park on surfaces of Cycles I and II match the stages developed on similar surfaces in the eastern Grand Canyon. In contrast, the more advanced stages are developed on surfaces much closer to the present river grade in the Granite Park area than in the eastern Grand Canyon or at Lees Ferry. For example, Stage III soil is ≤25 m above HWL at Granite Park (Fig. 6), but ≥100 to ~250 m in the upstream areas (Table 2). Similarly, Stage V soil is at ~60 m and ≥205 m elevations, respectively. These data show that downcutting rates over the last 500,000–600,000 yr in the Granite Park area were 0.0001 m/yr, versus 0.0004 m/yr upstream.

Most soils in the Grand Canyon did not form on deposits that can be dated directly. Ages of soil-carbonate stages have been approximated by ^{10}Be and ^{26}Al cosmogenic-radionuclide exposure geochronology for terraces and planation surfaces on which the soils have formed. The Granite Park area provides calibration of older soil-carbonate stages through association of stages IV and V with the precisely dated Black Ledge basalt flows. Together with extensive geomorphic mapping, many exposure-age determinations, and about 34 formal soil descriptions (Lucchitta *et al.*, 1995b; M. W. Caffee, S. W. Davis,

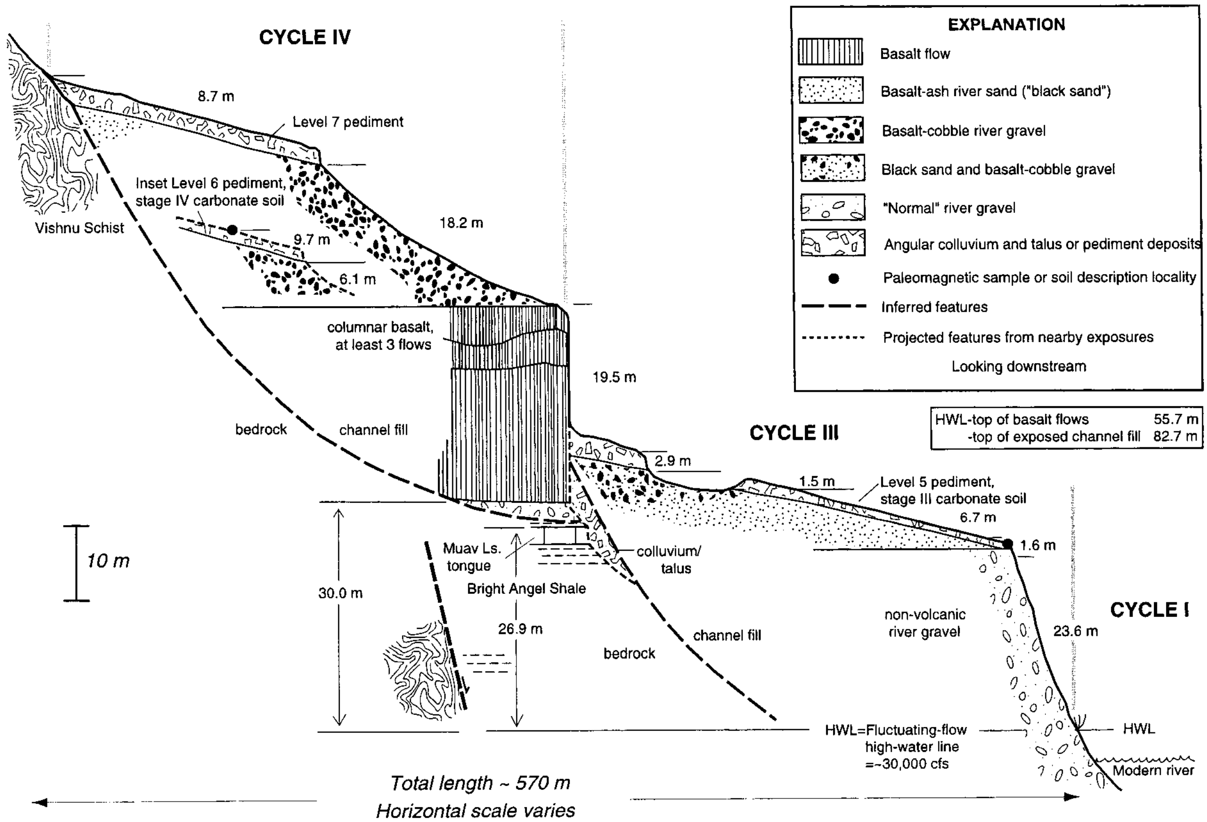

FIG. 6. Profile E, Granite Park, river left, River Mile 207.3. The bedrock fault, level 6 pediment, and underlying basalt–cobble gravel are projected from nearby exposures.

M. E. Davis, and I. Lucchitta, unpublished data), this establishes a framework for soil-carbonate ages that should be valid throughout the Grand Canyon, provided that differences in climate do not greatly affect the rate of soil-forming processes. Lees Ferry is at an altitude of 950 m, the Palisades–Unkar area at about 829 m, and Granite Park at about 470 m. Rainfall is low, and summer temperatures are above 38°C throughout the Grand Canyon. The framework also utilizes data from the Rainbow Plateau of Utah, at about 1400 m, where juniper and pinyon trees indicate greater precipitation and cooler climate.

TABLE 1
^{40}Ar–^{39}Ar Stepwise Laser-Fusion Ages of Black Ledge Basalt Flow

BGC[a] sample number	Age, yr (plateau, $\pm 1\sigma$)
GC-22-93	585,000 ± 14,000
GC-24-93	609,000 ± 6000
GC-22-93 and GC-24-93, weighted average	603,000 ± 8000
GC-26-93	604,000 ± 8000
GC-26b-93	607,000 ± 9000
GC-26-93 and GC-26b-93 weighted average	605,000 ± 8000
GC-29-93	525,000 ± 13,000
GC-34-93	559,000 ± 9000
GC-35-93	500,000 ± 7000
GC-29-93, GC-34-93 and GC-35-93 weighted average	524,000 ± 7000

[a] Berkeley Geochronology Center.

Exposure-age data for the eastern Grand Canyon are summarized in Table 2. A few stage IV carbonate soils have been described, but are not well dated. However, pediment surfaces with stage IV carbonate soils in the Rainbow Plateau, near Lake Powell, have yielded exposure ages ≥250,000 yr (Finkel *et al.*, 1994). This fits in well with the overall carbonate-stage chronology for the Grand Canyon region, so we infer that Stage IV carbonate soils on level 6 in the Granite Park area are of a similar age. In any case, their relation to the Black Ledge basalt flow sequence provides a local constraint on age.

Figure 7 shows the relation of soil carbonate stages V, IV, III, and II to the 600,000- and 525,000-yr-old basalts. The Stage V carbonate clearly postdates emplacement of both; the question is by how much. The 525,000-yr basalt is thin and within the black sand and basalt–cobble gravel directly above the main Black Ledge flows. Had there been a significant time interval between emplacement of the flow and sediment, one would expect erosion of the basalt and normal, polymict river sediments above the flow. In their absence, we infer that the

TABLE 2
Terrace Levels and Ages, Lees Ferry and Eastern Grand Canyon

Elevation above present grade (m)[a]	Age (10^3 yr B.P.)[b]	Paleofloodplain level?	Soil stage
10[c]	>5100 B.P.–1250 A.D.[d]	✓	I
>7[e]	26		
<32[f]	60		II
~25[c]	80	✓	II
40-45[c]	100	✓	Advanced II–III
~70[c]	206	Probably	
96[c]	≥213	✓	Advanced III
120[c]	~250[g]	✓	Advanced III
>205[c,e]	≥525[h]	✓	Eroded V

Note. Data from Lucchitta *et al.* (1995b), Caffee *et al.* (1994), and Lucchitta and Leopold (1999) and from unpublished material by Caffee, Davis, Finkel, and Lucchitta.

[a] Obtained by hand-assembling elevations and ages of discontinuous terrace remnants into groups.

[b] Each age reported is average of several determinations. Except as noted, all are ^{26}Al and ^{10}Be exposure ages run simultaneously for each sample. Results are not used when Al and Be ages for the same sample differ by more than 20%. Samples were collected from top of boulders on surfaces, so ages are surface ages. Determinations carried out by M. Caffee and R. Finkel, Center for Accelerator Mass Spectrometry, Lawrence Livermore Radiation Laboratory.

[c] Terraces of Colorado River. Terraces not so marked are on tributaries.

[d] Lower limit based on ^{14}C determinations by R. Finkel, as above. Base of unit considerably older because ≥7 m of deposits underlie lowest dated horizon. Upper limit based on presence of Pueblo II artifacts at top of unit and absence of Pueblo III material.

[e] Minimum value because top of terrace is eroded.

[f] Maximum value because it was determined on the lowest edge of the truncated sloping plantation surface that formerly extended farther down to paleofloodplain level.

[g] ^{10}Be only.

[h] Based on the presence of eroded Stage V carbonate soil, dated in western Grand Canyon at ~525,000 yr (this paper).

upper flow, the basalt–cobble gravel, and the black sand represent near-simultaneous, and probably catastrophic, events. At first, the river was overloaded and forced to aggrade rapidly. Once the events related to volcanism were over, the river was no longer overloaded and began downcutting energetically to reestablish its old grade. The rate presumably was high in the just-deposited and unconsolidated basalt–cobble gravel and

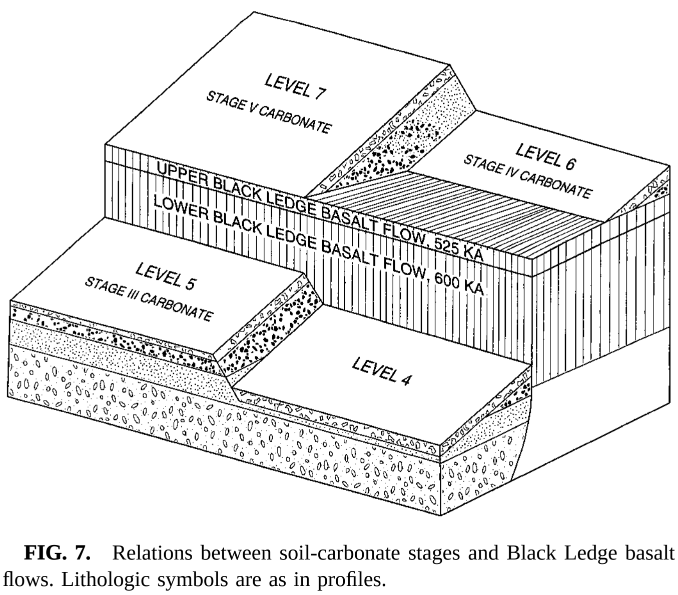

FIG. 7. Relations between soil-carbonate stages and Black Ledge basalt flows. Lithologic symbols are as in profiles.

black sand, which were rapidly cleared from the river channel. A similarly high rate is illustrated by the 10 m of downcutting and the widespread removal of the archeological unit in the ~750 yr since the end of deposition. The level 7 pediment and associated Stage V carbonate soil are graded to the top of the main flow sequence and represent the time when the river had regained this level after the disturbance represented by the younger flow and associated sediments. If, as we argue, the time represented by this disturbance was geologically short, the Stage V carbonate soil can be taken to be of the same age as the youngest basalt flow—525,000 yr. In contrast, the main flows were hard to cut through because of their toughness, thickness, and length, so the river probably was stuck on top of this basalt for a considerable time, as shown by level 6, which has a Stage IV carbonate yet is graded to a level not much below that of level 7.

Once the basalt was sliced through, the river continued downcutting during Cycle III, forming a new channel in bedrock below the basalt, then depositing the nonvolcanic gravel and the overlying basalt–cobble gravel and black sand, which reflect a post-Black Ledge volcanic event upstream. These were truncated by the level 5 surface, which has a Stage III carbonate. Since the Black Ledge basalt has a minimum age of 525,000 yr, and stage III carbonate soils have cosmogenic ages in the range of 100,000 to 250,000 yr (Table 2), the time represented by cutting through the basalt and the subsequent backfilling and pedimentation during Cycle III is measured in hundreds of thousands of years, much greater than the time taken to cut down through the Cycle IV gravel and sand to the top of the basalt.

In summary, basalt ages in Granite Park and exposure ages in the Grand Canyon yield the following framework for soil ages in the Granite Park area:

Stage V carbonate ~525,000 yr
Stage IV carbonate <525,000 yr, ≥250,000 yr
Stage III carbonate ≪525,000 yr, <250,000 yr, ≥100,000 yr
Stage II carbonate ≤100,000 yr, ~80,000 yr.

Processes

Whereas Cycles I (modern river), II (archeological unit), and III (nonvolcanic gravel) correspond to similar cycles well expressed elsewhere in the Grand Canyon, especially in the Palisades–Unkar area, Miles 65 to 73 (Lucchitta *et al.*, 1995b), Cycle IV, and the volcanic material in Cycle III attest to profound local changes in the river's activity resulting directly or indirectly from volcanism in the Vulcan's Throne–Whitmore Wash area upstream from Granite Park. The most significant aspect of the volcanism was the repeated cascading of lavas into the Grand Canyon. Each of the major cascades produced dams that ponded the river, which in turn resulted in deposition of lacustrine beds upstream from the dams (Hamblin, 1994) and significantly affected sedimentation downstream. The Granite Park sections help decipher these processes.

The monolithologic basalt–cobble gravel and basaltic sand that overlie and are inset into the basalt of Cycle IV and are interbedded with the nonvolcanic gravel of Cycle III offer a unique problem in interpretation. A mechanism must be found that allows deposition of volcanic debris while overwhelming the material that normally forms the channel fill of the Colorado River and is brought in axially by the river and laterally by tributaries.

The only realistic way to exclude the normal material is to temporarily overload the river with locally derived volcanic material, either during an eruption or later through the breaching of lava dams. The overload would cause the river to build up its grade, trapping nonvolcanic material at the upstream end of the aggraded area in both the main river and the tributaries.

We propose that overloading of the Colorado River occurred during eruptions with direct fall of ash into the river, remobilization of ash that blanketed nearby terrain, and perhaps basaltic debris produced by quenching and thermal shattering of flows in contact with river water. Many vents in the Vulcan's Throne–Whitmore Wash area are cinder cones (Hamblin, 1994), whose dominant activity is venting tephra, the finer fraction of which forms an ash blanket of considerable areal extent and volume (Macdonald, 1972). The blanket, unconsolidated and not stabilized by vegetation, soon finds its way into drainage systems, which are then overloaded and become aggrading braided streams while the supply of ash lasts (Segerstrom, 1960; Kuenzi *et al.*, 1979; Vessel and Davies, 1981; Smith, 1991; Inbar *et al.*, 1994). This is likely to be a very fast process, especially when debris flows are involved in bringing volcanic ash to a drainage, when meters of ash can be deposited in a matter of days, weeks, or months. Debris flows are common in the Grand Canyon, whether in the geologic record (Lucchitta *et al.*, 1995b) or as present-day processes (Webb *et al.*, 1989). As the ash blanket becomes depleted or stabilized by vegetation, aggradation of streams slows down or stops. The black sand deposits in Granite Park are likely to be the record of such events, especially direct ashfall and erosion of ash blankets. If mudflows made a significant contribution of material to the system, the Colorado River winnowed the fine fraction and transported it beyond the Granite Park area.

Another way to overload the river is represented by the basalt–cobble gravel, a high-energy deposit. We believe that the gravel in part represents erosion of thermally shocked and fractured basalt flows, but mostly the overtopping of basalt dams and consequent vigorous erosion of the basalt, probably by plunge-pool action and headward erosion, as proposed by Hamblin (1994). This erosion would cut and scour the basalt in the area of the dam, but the products of erosion would overload the river downstream from the dam, resulting in rapid deposition of coarse material.

In summary, we infer that the black sand deposits signal eruptions, whereas basalt–cobble gravel deposits signal the breaching of lava dams following eruptions. Under ideal conditions, black sand should therefore underlie basalt–cobble gravel if they both result from a single eruption. This indeed is the case in three of our sections, but in other cases relations are less simple; these deposits may represent multiple and near-simultaneous eruptions, so that gravel resulting from breaching of a dam produced from one volcanic eruption could be intermixed with black sand resulting from another eruption.

The basalt–cobble gravel and basalt sand represent valuable observational evidence of how the Colorado River responds to changes in its load: vigorous aggradation as long as a temporary overload exists and equally vigorous downcutting once the overload ends. The important point here is that vigorous downcutting can be triggered merely by the end of an overload rather than by underloading relative to some initial conditions. In the case of Cycle IV in the Granite Park area, the aggradation and downcutting amounted to at least 27 m (Fig. 6). There is no direct way to determine the rate at which the downcutting took place. The overall rate from the time when the Black Ledge basalt flow was emplaced to today is 1.6 cm/1000 yr, but the actual rate at which downcutting took place is much greater because this time interval includes several periods of aggradation, incision, and stasis. An estimate for the rate of downcutting through the unconsolidated basaltic gravel and ash is provided by the archeological unit, which has been incised 8 to 10 m in approximately 700 yr, a rate of 1140 to 1430 cm/1000 yr. Conversely, the genesis of the archeological unit is clarified by the temporary overload and resulting aggradation well expressed in the Granite Park area and caused by volcanic events represented by the basaltic sand and gravel.

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